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A Coupled Atmosphere-Wave-Ocean Framework for High-Resolution Modeling of Tropical Cyclones and Coastal Storms

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1. Introduction

Recent advances in high-resolution modeling of tropical cyclones (TCs) with explicitly resolved TC inner core region have revealed many complex features in the high gradient area of a hurricane eye and eyewall. It has also highlighted the complexity of the air-sea interaction in TCs. Observations from the Coupled Boundary Layer Air-Sea Transfer (CBLAST)-Hurricane field program show that TC induced ocean surface waves are highly asymmetric. Surface stress is mainly determined by the surface waves, which can affect TC structure and intensity significantly. A TC draws energy from the ocean surface, while cools the ocean by wind-induced surface fluxes and vertical mixing in the upper ocean. To understand the structure and intensity change of TCs, the atmosphere, ocean surface waves, and ocean circulation need to be treated as a fully coupled system. Over the last a few decades, because of the limited computer power and lack of observations over the ocean, development of high-resolution, fully coupled models has not been practical. However, rapid increase in computer power and recent advance in technology in observations have made it possible to develop and test a fully coupled atmosphere-wave-ocean modeling framework for high-resolution TC and coastal storm predictions. We aim to develop a set of coupling parameterizations that are general enough for various atmosphere and ocean model components to be interchangeable. For the future development, we plan to the Earth System Modeling Framework (ESMF) for the generalized modeling system. Here we focus mostly on the coupled model simulations of Atlantic hurricanes using the coupling parameterizations developed at RSMAS/U. Miami, which have been tested in a number of storms including Hurricanes Bonnie (1998), Floyd (1999), Fabian (2003), and Frances (2004). Frances is one of the best observed storms during CBLAST-Hurricane 2004 field program. Model simulations are compared and evaluated with the best track data from the National Hurricane Center (NHC), surface winds, surface wave spectra, air-sea fluxes, ocean temperature and salinity profiles, and SST from various in-situ, airborne, and satellite observations.

2. Coupled Atmosphere-Wave-Ocean Modeling System

2.1 Atmospheric models

The atmosphere models in the coupled modeling system are the Fifth Generation of the Penn State University-National Center for Atmospheric Research atmospheric nonhydrostatic mesoscale model (MM5) (Dudhia 1993, Grell et al. 1994) and the Weather Research and Forecasting (WRF) model. For studying hurricanes and coastal storms, we have developed a vortex-following nested grid that allows for long integration (5-7 days or longer) of the model with cloud-resolving resolution of 1-2 km in the inner most domain (Tenerelli and Chen 2001, Rogers et al. 2003, Chen and Tenerelli 2005). This feature is currently in the process of being implemented in WRF. In this study, we use 4-level nests with 45, 15, 5, and 1.67km resolutions, respectively.

2.2 Wave Models

The ocean surface wave models are the third-generation wave model, namely the NOAA WAVEWATCH III (or WW3) developed by Tolman (1991) for wind waves on slowly varying, unsteady and inhomogeneous depths and currents, and a new parametric wave model developed by Donelan (2004a). In this study, we use WW3 using the action density wave spectrum with 25 frequencies logarithmically spaced from 0.0418 to 0.41 Hz and 48 directional bands.

2.3 Ocean models

The ocean circulation models used in the coupled system are the WHOI's three-dimentional upper ocean model with the PWP mixing scheme (3DUOM, Price 1994) and the U. Miami/NRL Hybrid Coordinate Ocean Model (HYCOM, Bleck et al. 2002). The ocean model grid resolution vary from 1/12 degree in HYCOM to 15 km in 3DUCOM.

2.4 Coupling framework

A generic coupled modeling framework is demonstrated in a schematic diagram in Fig. 1. We have developed physically-based couplers between each of the model components. Most previous coupled parameterizations do not work well in high-wind conditions. One of the issues is related to the wind-wave coupling is critically depended on the high frequency of the wave spectra that cannot be fully resolved by the current wave models. We first developed a new wind-wave coupling method that parameterizes the special tail and integrates the total wave spectra to calculate surface stress (Chen et al. 2004). It is based the lab measurements described in Donelan et al. (2004b). Another issue is related to the lack of accurate SST field from current ocean models on short time and small spatial scales, which is required for hurricane prediction. Before an improved data assimilation is available, we have adopted a method that uses a combined high-resolution satellite observed SST and model produced SST anomaly for the coupled system. It works well in the highly wind-driven environment.

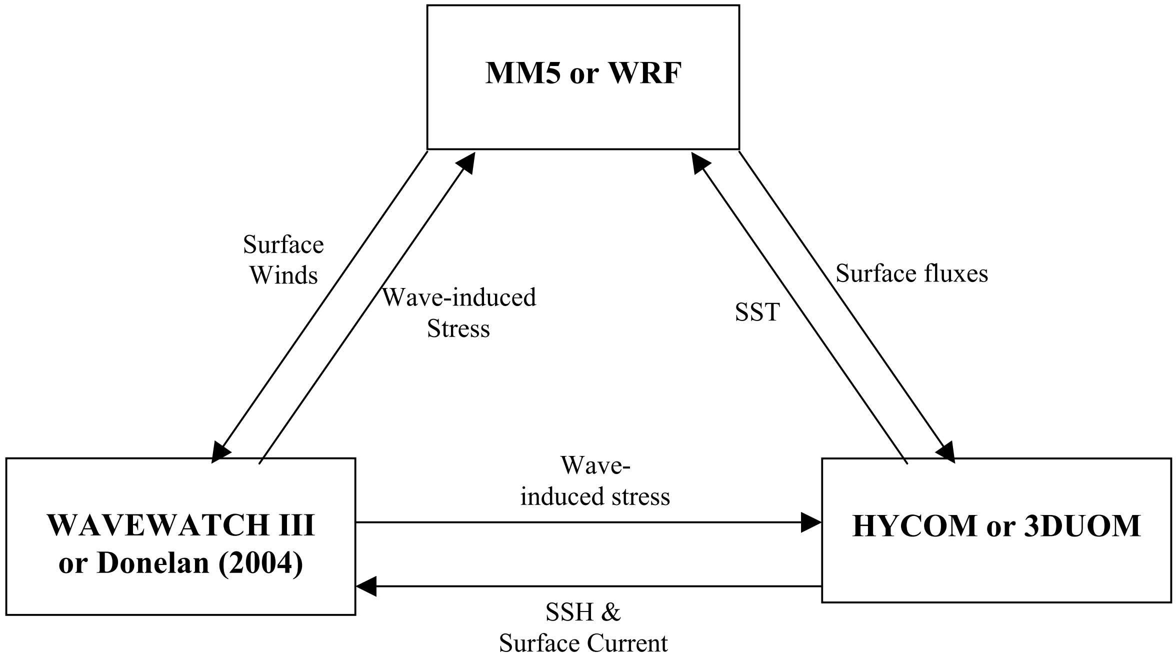

Fig. 1 A schematic of the coupled atmosphere-wave-ocean modeling framework.

3. Hurricane Frances (2004)

The coupled modeling system has have tested in a number of Atlantic hurricanes including Bonnie (1998), Floyd (1999), Fabian (2003), and Frances (2004). Here we present some results from Hurricanes Frances (2004) that one of the best observed storms during the CBLAST-Hurricane 2004 field program. To better understand the effects of air-sea coupling on hurricanes, we conducted an uncoupled control simulation using MM5 only. Fig.2 shows the comparisons of model simulated tracks and the minimum sea-level-pressure (SLP) with the best track data from the National Hurricane Center (NHC). The model simulated tracks are very close to that of observed (Fig. 2a). The coupled simulation is slightly better near the landfall then the uncoupled MM5. However, the coupled model improves the model simulated storm intensity significantly over the uncoupled MM5. It is mostly because of the storm induced cooling due to vertical mixing in the upper ocean in the coupled model, whereas the uncoupled MM5 uses a constant SST through out of the simulation. The storm-induced cold wake in the SST is well simulated in the coupled model compared with the satellite observations (Fig. 3). The maximum cool is to the rear right of the storm as observed in Frances and many other storms previously.

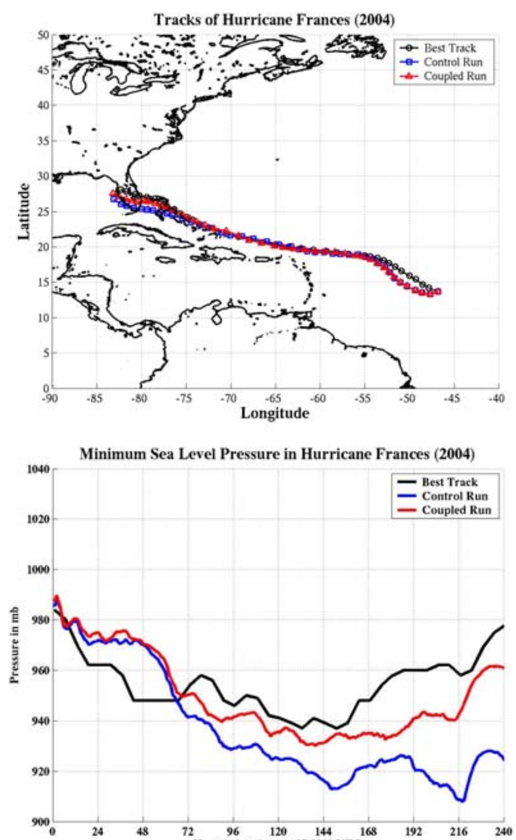

Fig. 2 Model simulated (a) storm tracks (blue: MM5 and red: coupled), and (b) minimum SLP of Hurricane Frances in comparison with the NHC best track data (black) over a 10-day period from 0000 UTC on 27 August – 0000 UTC on 6 September 2004.

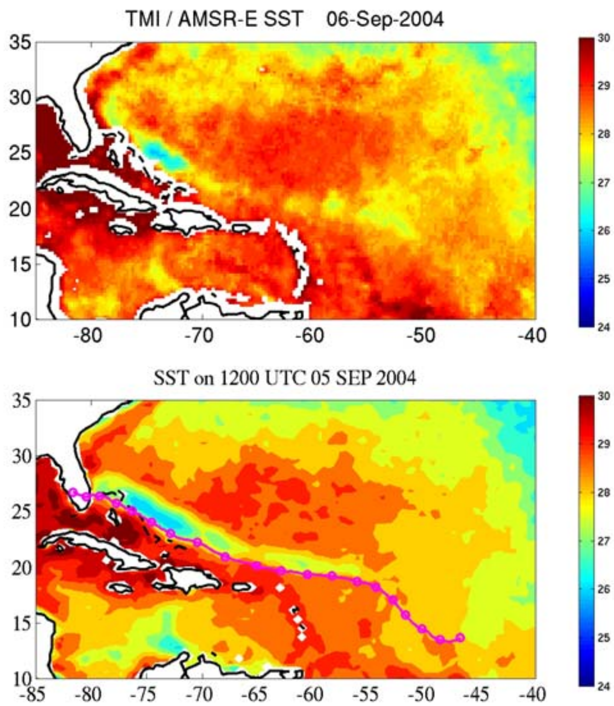

Fig. 3 Sea surface temperature (SST) fields after Hurricane Frances' passage, (a) observed from the combined TRMM TMI and AMSR-E satellite data on 6 September, and (b) coupled model simulation from 27 August – 6 September 2004.

The storm-induced surface wave field is high complex and asymmetric around a hurricane. It is clearly evident in the coupled simulation of Hurricane Frances, in terms of both significant wave height (SWH) and wave length (Fig. 4). The highest SWH and largest wave length are found in the front right quadrant as observed in CBLAST-Hurricane field program and previously by Walsh et al. (2002). These characteristics in the wave fields will produce a relatively weaker surface stress in the front right quadrant and a stronger stress in the rear left quadrant of the storm.

On the other hand, the SST cooling is also asymmetric around the storm. The combined effect of the atmosphere-wave-ocean coupling gives a rise in the asymmetry in the air-sea fluxes as shown in Fig. 5. The uncoupled MM5 simulation produced a more symmetric net heat flux (Fig. 5a) compared to that of coupled model simulation (Fig. 5b). The asymmetry in surface heat flux has also been observed in CBLAST-Hurricane 2004.

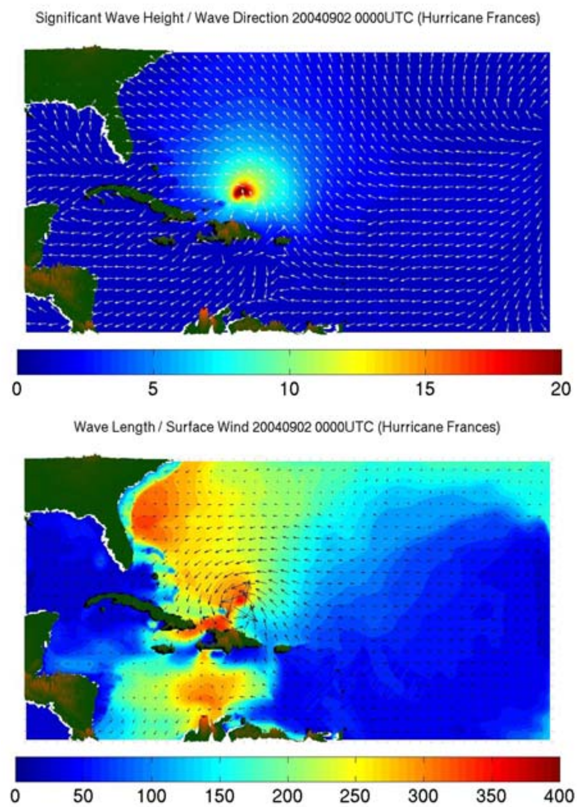

Fig. 4 Sea surface significant wave height (a) and mean wavelength (b) from coupled simulation.

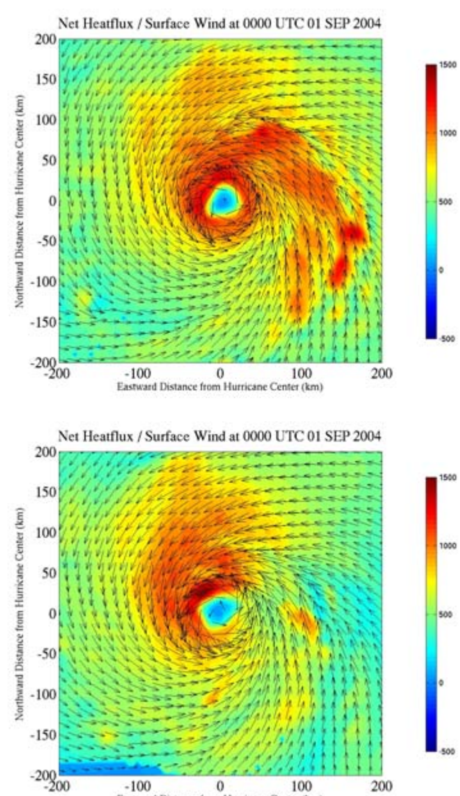

Fig. 5 The total surface heat flux from (a) uncoupled MM5 and (b) coupled simulations at 0000 UTC on 1 September 2004.

4. Conclusions

The coupled atmosphere-wave-ocean modeling system has been tested successively in a number of Atlantic hurricanes. Model simulations are compared and evaluated with available in-situ and satellite observations. In general, the coupled model improves model simulated storm structure, air-sea fluxes, and storm intensity changes compared to that uncoupled atmospheric model simulations. The coupled modeling framework with physically based coupling parameterizations allows the flexibility of using various model components. We are in the process of working toward using the ESMF in this coupled system.

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